Investigations on the semileptonic decay K_{e3} at the NA48 experiment*

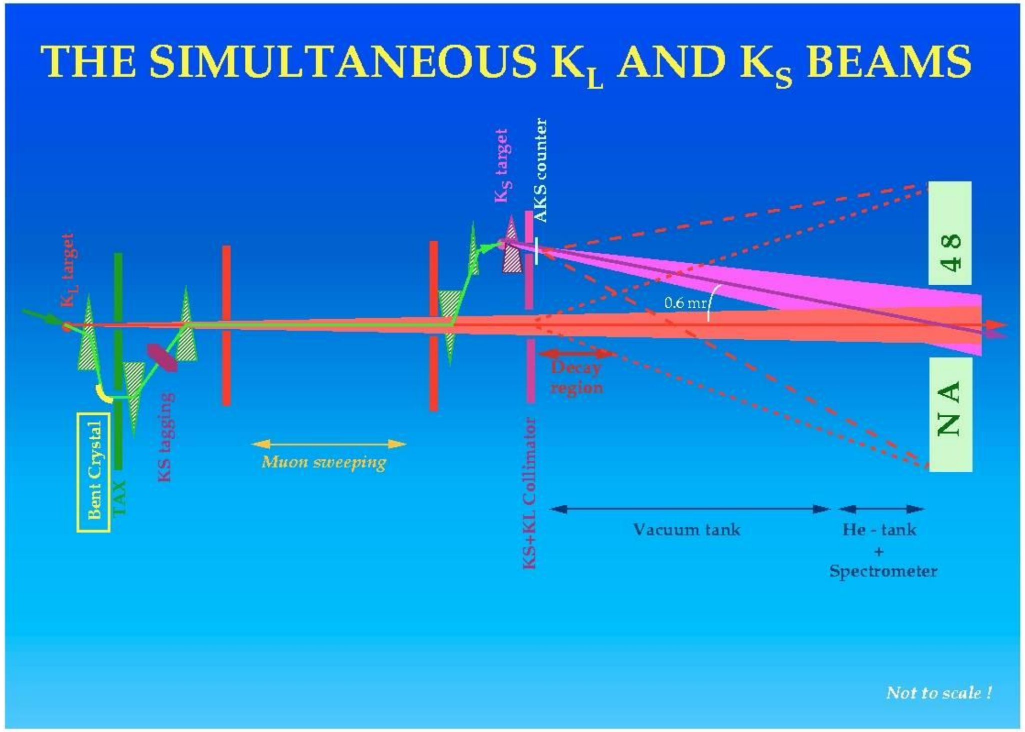
Stoyan Stoynev

University of Sofia

*Based on the Kaon 2005 Workshop and thesis (12.05.05.) presentations

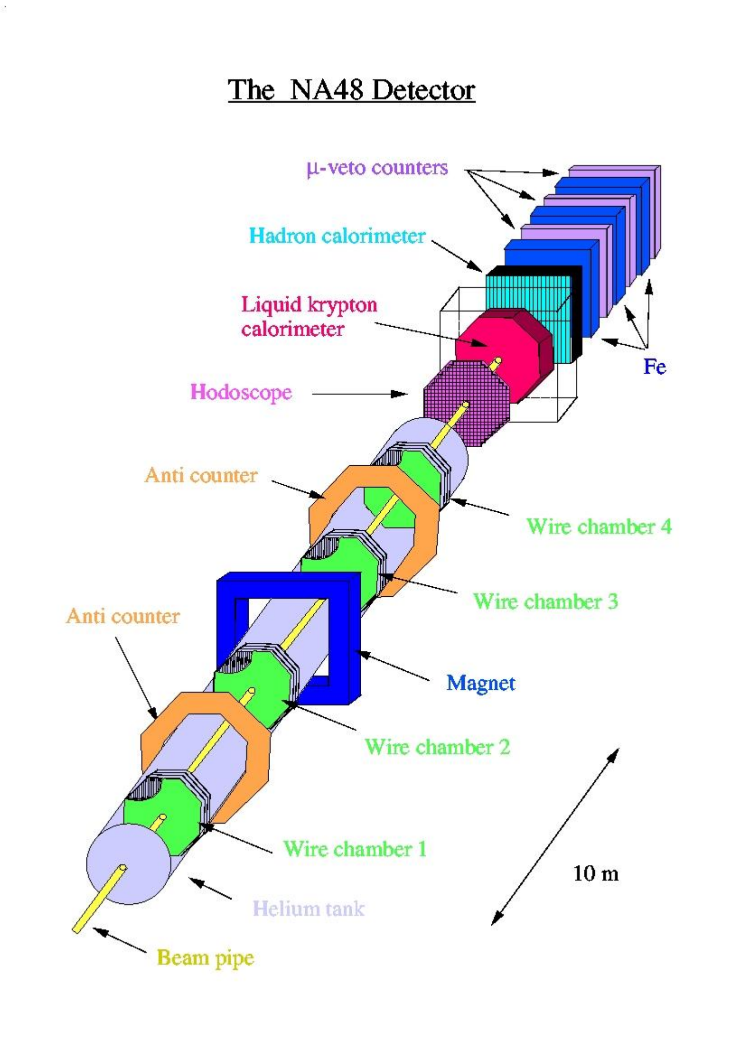
The NA48 experiment

- Simultaneous near collinear beams of K_L and K_S with average energy ~110 GeV



- Designed for a measurement of direct CP-violation in the K^0 system

Detector setup



- Magnetic spectrometer (two drift chambers DCH before and two DCH after the spectrometer magnet)

$$\frac{dp}{p} = (0.48 + 0.009 \times p)\%$$

- Hodoscope CHOD (time resolution – 200 ps per track)
- Homogenous electromagnetic calorimeter LKr

$$\frac{dE}{E} = \left(\frac{3.2}{\sqrt{E}} + \frac{9.0}{E} + 0.42\right)\%$$

- Hadron calorimeter HAC
- Muon veto system MUV

K_{e3} form factors

- Semileptonic decays
  - give information about the nature of weak interactions
  - allow to test models describing hadron interactions at a small momentum transfer (ChPT)

- Theoretical framework
  - locality of weak interactions
  - μ-*e* universality
  - two component neutrino
  - $\Delta I=1/2$ rule (I – isospin)

K_{e3} Dalitz plot

q Dalitz plot density:

$$r(E_p, E_e) = m_K f_+(q^2)\left(2\,E_e E_n - m_K E'_p\right) + m_K^2 E'_p\left(f_S + \frac{1}{m_K}(E_n - E_e) f_T\right)$$

m_i – mass of the particle i, E_i - energy of i in the COM,

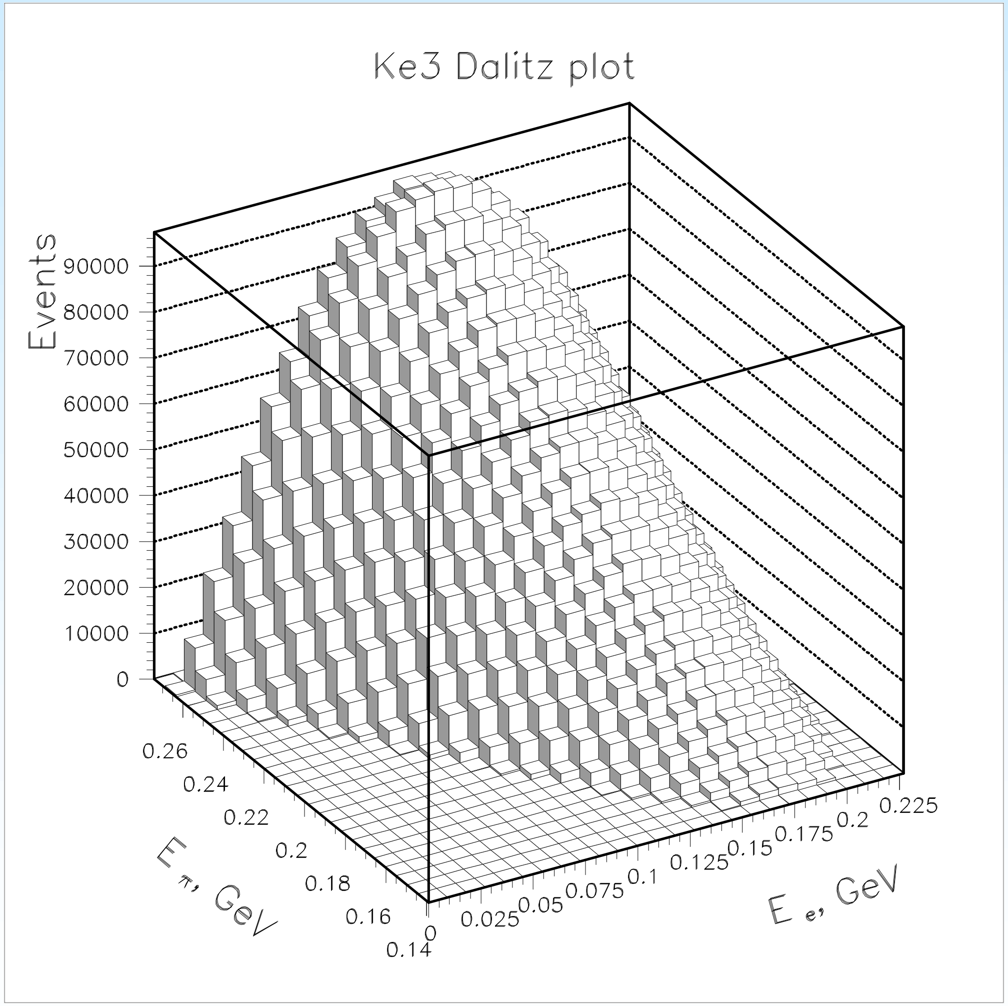
$$E'_p = \frac{m_K^2 + m_p^2}{2\,m_K} - E_p \qquad q^2 = (p_K - p_p)^2$$

f_+, f_S, f_T – vector, scalar and tensor form factors;

f_S and f_T are 0 according to the SM!

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_V^2}} = f_+(0)\left(1 + l_+ \frac{q^2}{m_p^2} + l'_+ \frac{q^4}{m_p^4} + \ldots\right)$$

K_{e3} Dalitz plot – a view



$$\propto r(E_p, E_e)$$

Experimental data and MC simulation

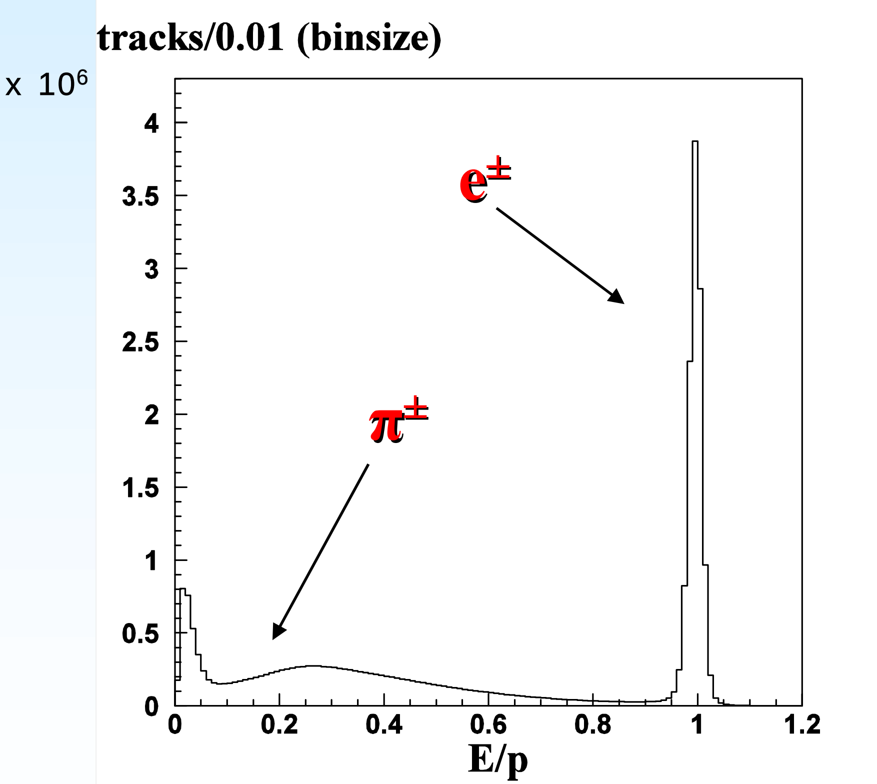
- Experimental data
  - three day run with K_L beam – September 1999
  - simple trigger (2 tracks)
  - ~ 2 TB data recorded (~100 million decays to charged particles)
- MC simulation
  - MC based on GEANT
  - radiative corrections in K_{e3} using Ginsberg calculations and PHOTOS (real photon events)

K_{e3} selection

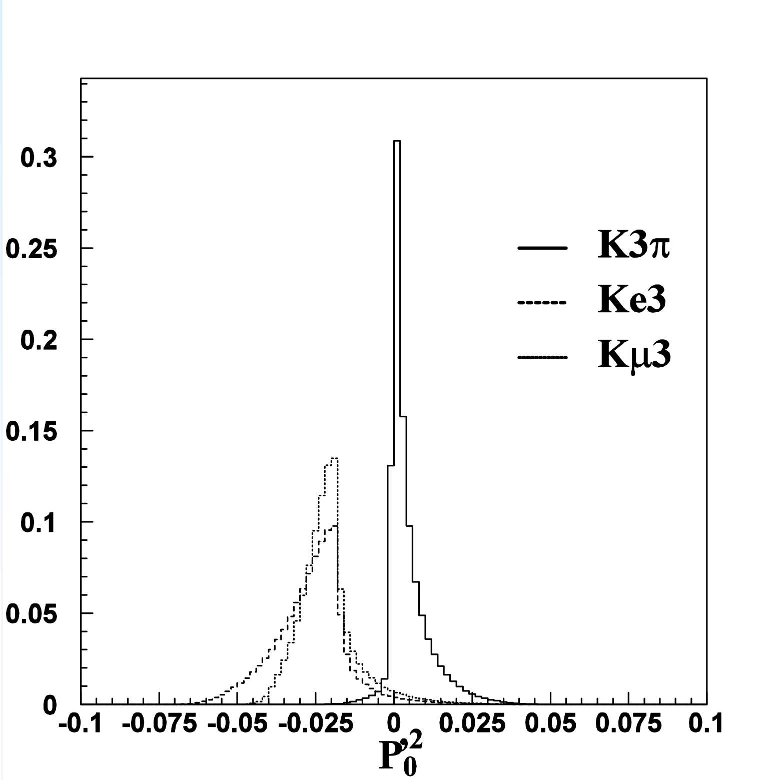
- Two tracks with different charges coming from a common vertex
- Time difference of the tracks < 6 ns
- Minimal distance between tracks < 3 cm
- Vertex located in the decay region : $6 \text{ m} < z < 34 \text{ m}$
- Tracks in the detectors aperture
- No MUV signal around the event time ($\pm$ 6 ns)
- Minimal momentum of each track $p_{min} = 10$ GeV
- Minimal distance between tracks in LKr $D_{lkr} = 25$ cm
- $0.93 < E/p < 1.1$ for one of the tracks ($e^{\pm}$) and $E/p < 0.9$ for the other one ($\pi^{\pm}$)
- $P_0'^2 < -0.004$ (against $K_{3\pi}$ background)
- $60 \text{ GeV} < E_K < 180 \text{ GeV}$

Particle and mode identifications

E/p for 2-track events (data)

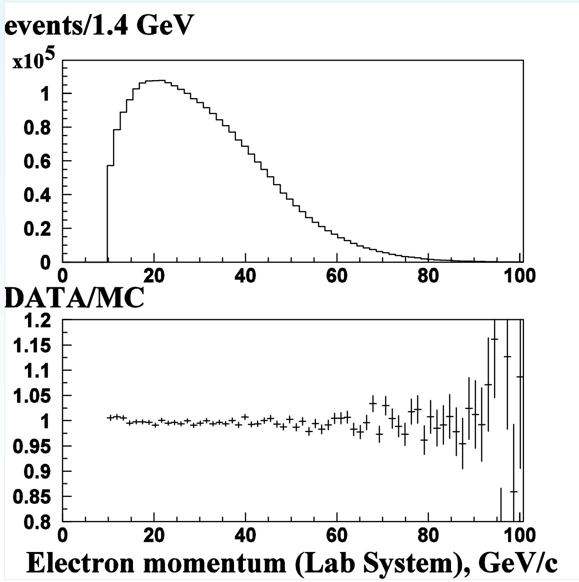


$P_0'^2$ for the main decay modes (normalized MC)

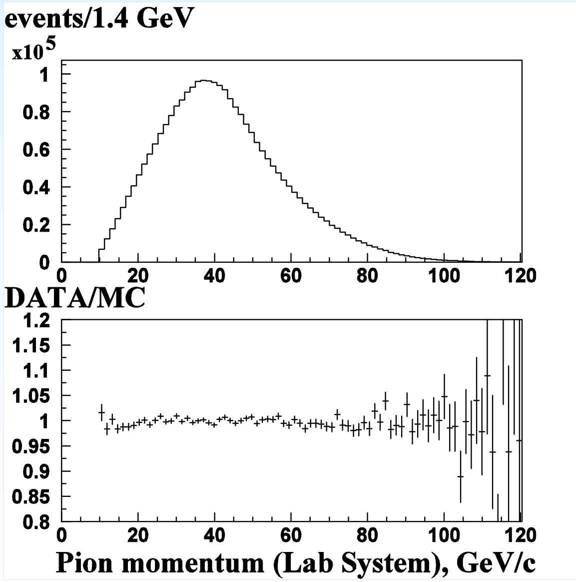


Data and MC comparison

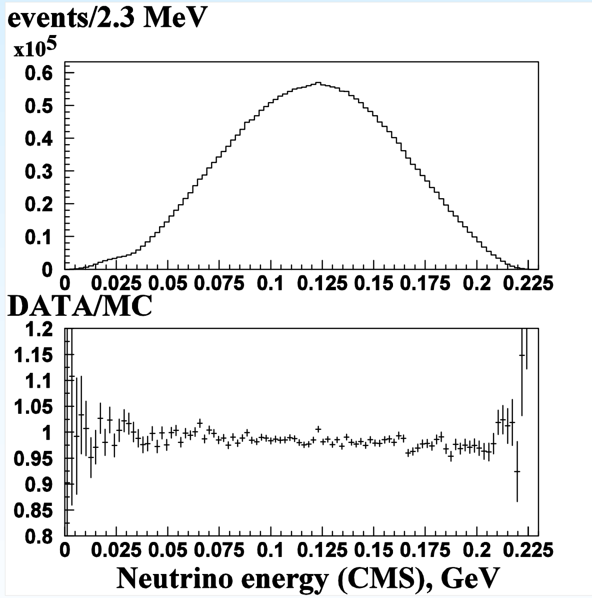
Electron momentum



Pion momentum



Neutrino momentum in the COM



Data analysis

- The momentum of the kaon is reconstructed to a two-fold ambiguity (due to escaped neutrino)
- Both solutions are used in the analysis
- Extraction of λ_+ is fulfilled by fitting the distribution $N(q_1^2, q_2^2)$ - i=1,2 stands for the 2 solutions
- Extraction of the three form factors is fulfilled by fitting the distribution $N(q_1^2, q_2^2, E_\nu^*)$ - E_ν^* is known unambiguously

Fitting method

- The method used allows to extract parameters from multi-dimensional data distributions
- The method is based on the Loglikelihood technique
- It takes into account Poisson fluctuations in the regions with small number of events
- The statistical uncertainty includes both experimental and MC data

Background and systematic uncertainties

Bg	$K_{\mu 3}$	$K_{3\pi}$	K_{e4}	K_{e3} (misidentification)
	$<1 \times 10^{-4}$	3×10^{-5}	2×10^{-5}	2×10^{-5}

	λ, f_S, f_T - fit			λ - fit
Source of syst.	$\Delta\lambda_+$, 10^{-4}	$\Delta\lvert f_S/f_+(0)\rvert$	$\Delta\lvert f_T/f_+(0\rvert$	$\Delta\lambda_+$, 10^{-4}
K_L spectrum	±8.0	±0.001	±0.005	±7.0
E,p calibration	±2.0	±0.001	±0.005	±2.0
Geometrical ineff.	±5.0	±0.007	±0.015	±4.0
D_{lkr}	±4.5	±0.004	±0.005	±2.5

Systematic uncertainties

	λ, f_S, f_T - fit			λ - fit
Source of syst.	$\Delta\lambda_+$, 10^{-4}	$\Delta\lvert f_S/f_+(0)\rvert$	$\Delta\lvert f_T/f_+(0)\rvert$	$\Delta\lambda_+$, 10^{-4}
p_{min}	**±2.5**	**±0.004**	**± 0.010**	**±1.5**
E/p	**±3.5**	**±0.002**	**± 0.010**	**±3.5**
Accidentals	**±3.0**	**±0.001**	**± 0.005**	**±2.5**
Trigger ineff.	**±1.5**	**±0.002**	**± 0.005**	**±2.5**
MUV ineff.	**±2.0**	**±0.002**	**± 0.005**	**±2.0**
$P_0'^2$ ("bg. ineff.")	**±2.0**	**±0.003**	**± 0.005**	**±1.0**
Bin width (resolution)	**±4.0**	**±0.005**	**± 0.010**	**±1.0**
Total	**± 13**	**±0.012**	**± 0.03**	**± 11**

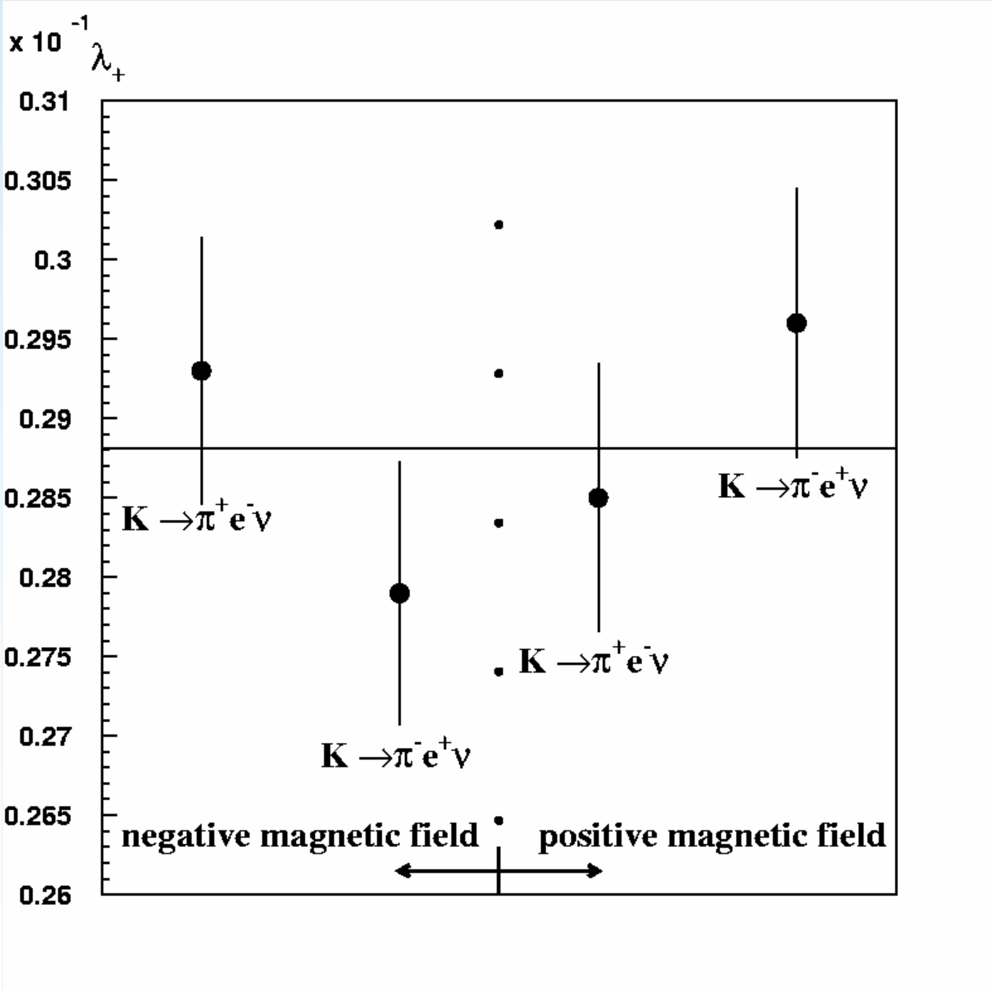
Results

λ_+	$\lvert f_S/f_+(0)\rvert$	$\lvert f_T/f_+(0)\rvert$
0.0284	0.015	0.05
± 0.0007 (stat.)	$^{+0.007}_{-0.010}$ (stat.)	$^{+0.03}_{-0.04}$ (stat.)
± 0.0013 (syst.)	± 0.012 (syst.)	± 0.03 (syst.)

linear fit | **quadratic fit** | **polar fit**

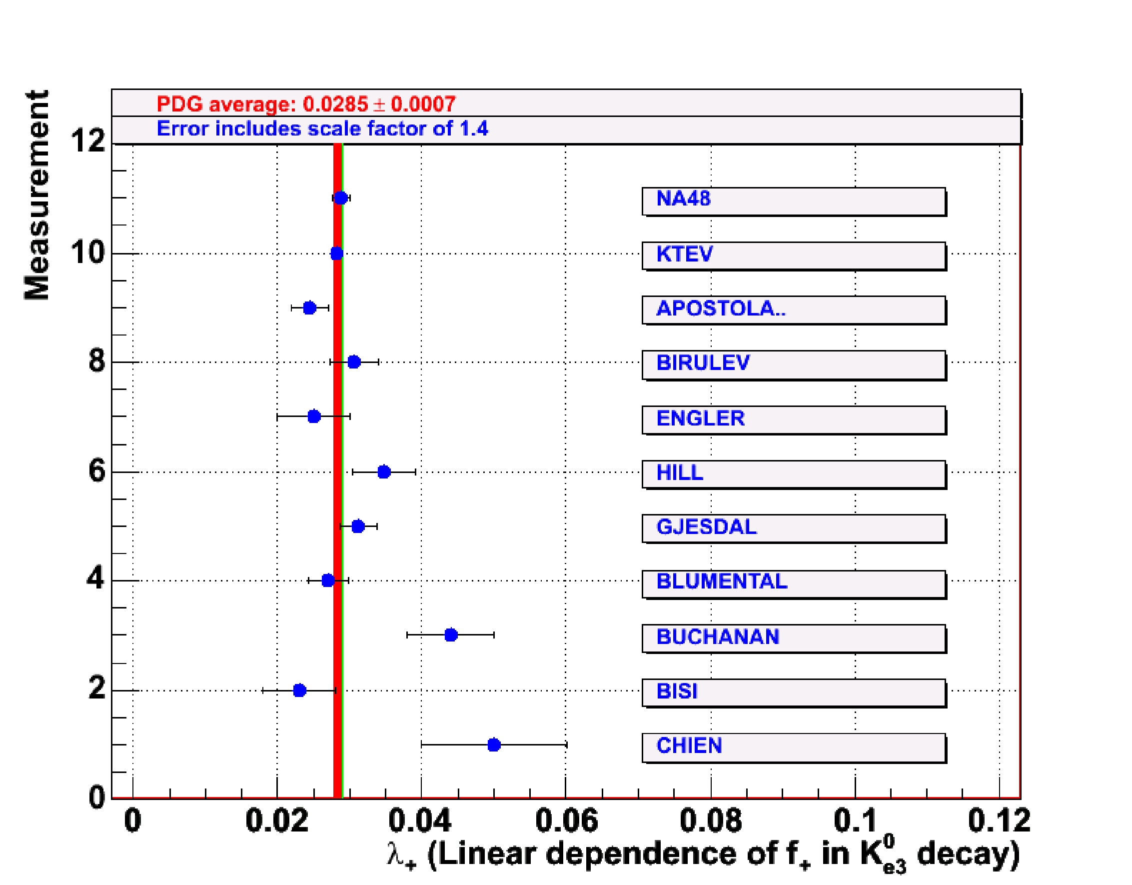
λ_+	λ_+	λ'_+	M_V, MeV
0.0288	0.0280	0.0002	859
± 0.0005 (stat.)	± 0.0019 (stat.)	± 0.0004 (stat.)	$\pm$ 18 (full)
± 0.0011 (syst.)	± 0.0015 (syst.)	± 0.0002 (syst.)	

“Differential” results for the slope



- Slope of the vector form factor at different polarities of the spectrometer magnet

World results



NA48:

$f_S/f_+(0) < 0.028$

$f_T/f_+(0) < 0.09$

PDG:

$f_S/f_+(0) < 0.04$

$f_T/f_+(0) < 0.23$

Radiative $K_{e3\gamma}$ branching ratio

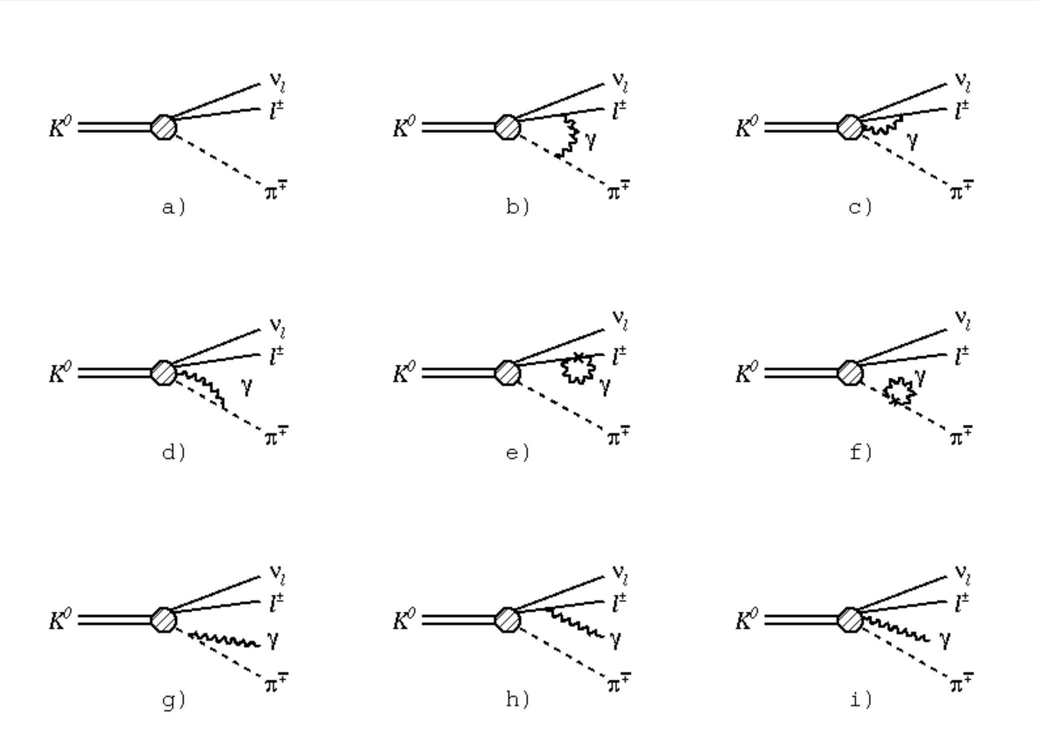
- Radiative semileptonic decays
  - give important information about the structure of the decaying particle
  - allow to test models describing hadron interactions at a small momentum transfer (ChPT)

- Radiative Branching ratio:

$$R = \frac{\Gamma(K_{e3g}, E_g^* > 30\,MeV, q_{eg}^* > 20^\circ)}{\Gamma(K_{e3})}$$

- Experimental status (before the NA48 result):
  - only one high precision measurement (~1.5%)
  - this measurement is in disagreement with theoretical predictions (~3σ)

Radiative corrections



- Feynman graphs of the radiative corrections in K^0_{e3} (first order in α)

(a) zero order process (g)-(h) IB

(b)-(f) virtual processes (i) DE

$K_{e3\gamma}$ selection

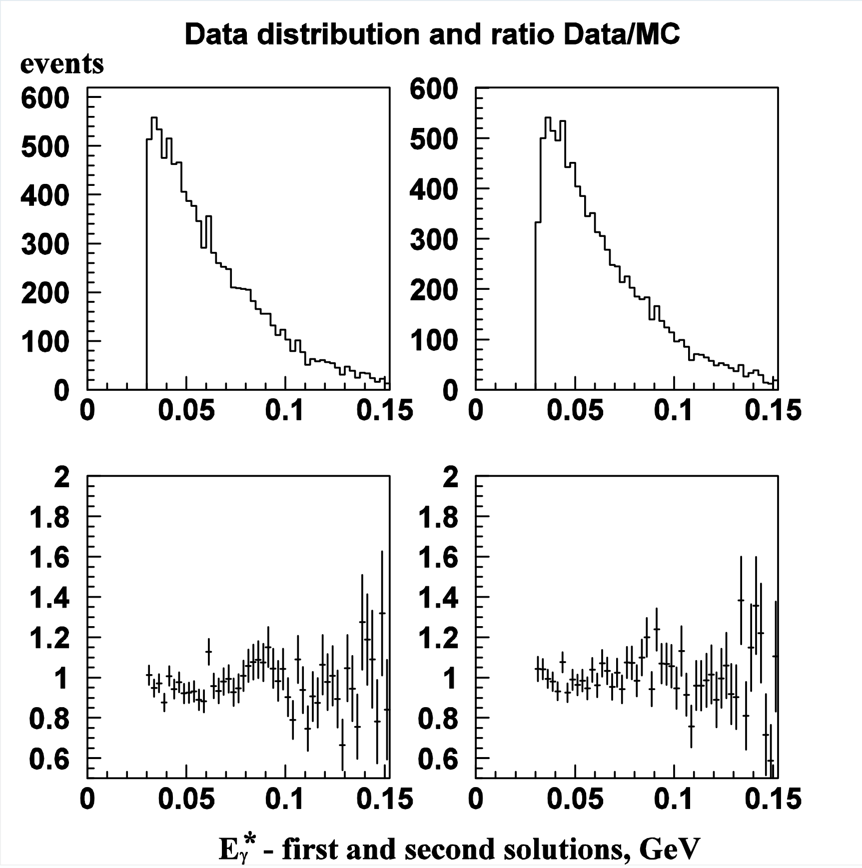
q K_{e3} selection

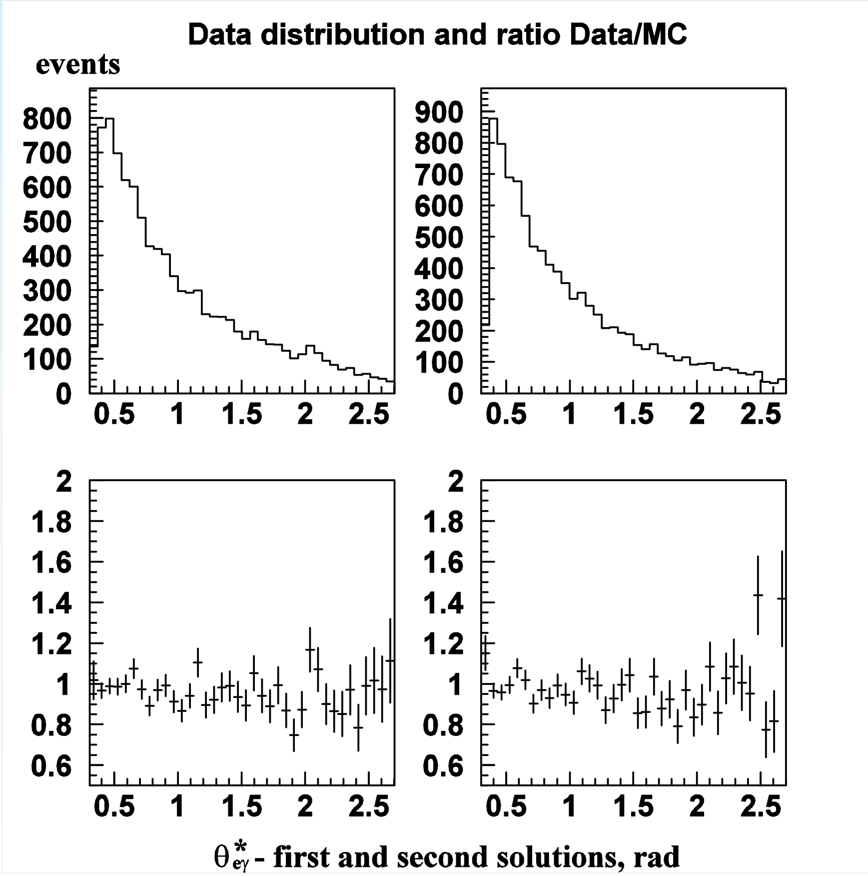
+

q One γ-candidate such as:

- F Distance between the photon and the pion entrance points in LKr > 55 cm
- F Distance between the photon and the electron entrance points in LKr > 6 cm
- F Distance between the photon and the z-axis (at LKr) > 16 cm
- F Energy of the photon > 4 GeV
- F Time difference between the photon and the (charged) event time < 6 ns
- F $(E^*_\gamma)_i$ > 30 MeV, $(\theta_{e\gamma})_i > 20\,^o$; i=1,2

Data and MC comparison





Data analysis

- Calculations

$$R = \frac{\Gamma(K_{e3g}, E_g^* > 30MeV, q_{eg}^* > 20^\circ)}{\Gamma(K_{e3})} = \frac{N(K_{e3g})Acc(K_{e3})}{N(K_{e3})Acc(K_{e3g})} C_M$$

  - C_M=0.9995 – takes into account the small difference observed in the number of extra clusters in LKr between data and MC
  - Acc(Ke3) = (17.28±0.01)% - acceptance of K_{e3}
  - Acc(Ke3γ) = (6.08±0.03)% - acceptance of $K_{e3\gamma}$

- Backgrounds and accidentals (in % of the $K_{e3\gamma}$ events)
  - from K_{e4} : 0.4±0.2
  - from $K_{3\pi}$: $0.2^{+0.3}_{-0.2}$
  - accidentals: $0.1^{+0.2}_{-0.1}$

Systematic uncertainties

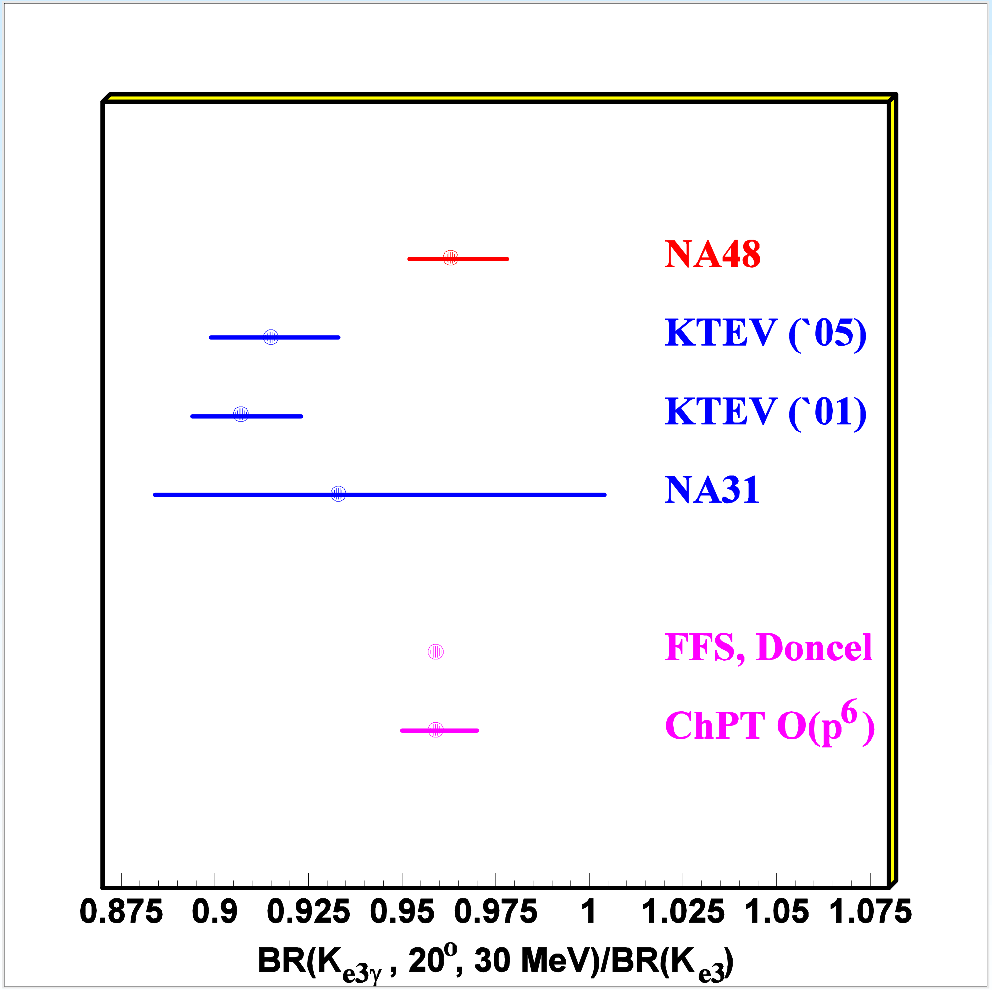
Source	$\Delta R/R \times 10^{-3}$
K_L spectrum	$^{+6}_{-3}$
$K_{e3\gamma}$ selection (acc)	± 5
Bg uncertainties	$^{+4}_{-3}$
K_{e3} selection (acc)	± 5
Accidentals	$^{+2}_{-1}$
Form factor	± 1
Total	$^{+11}_{-9}$

Results

- Number of reconstructed $K_{e3\gamma}$ decays: 18 977
- Number of reconstructed K_{e3} decays: 5.994 million
- Radiative branching ratio:

$$R = 0.964 \pm 0.008^{+0.011}_{-0.009} = 0.964^{+0.014}_{-0.012}$$

Compared results



Experimental results

Theoretical results

K_{e3} branching fraction

- Allow extraction of the V_{us} matrix element

$$|V_{us}|f_+(0) = \sqrt{\frac{128\,p^3\,\Gamma(K^0_{e3})}{G_F^2\,m^5_{K^0}\,S_{EW}\,I_{K^0}}}$$

G_F - Fermi constant, S_{EW} – electro-weak correction, I_K – phase space integral

- There is a vagueness around the branching fractions of the main decay modes of the K_L after latest experimental measurements

Strategy for the $\Gamma(K_{e3})$ extraction

- Measurement of the ratio:

$$R_e = \frac{Br(K_{e3})}{Br(K \rightarrow 2-tracks)},$$

$Br(x)$ – branching fraction of the decay x

- Using the relation:

$$Br(K \rightarrow 2-tracks) =$$
$$1 - Br(K_{3\pi^0}) - Br(K_{2\pi^0}) - Br(K_{\gamma\gamma}) + Br(K_{\pi^0\pi^0\pi^0_D}) - Br(K \rightarrow 4-traks) =$$
$$1.0048 - Br(K_{3\pi^0}),$$

then

$$Br(K_{e3}) = R_e[1.0048 - Br(K_{3\pi^0})]$$

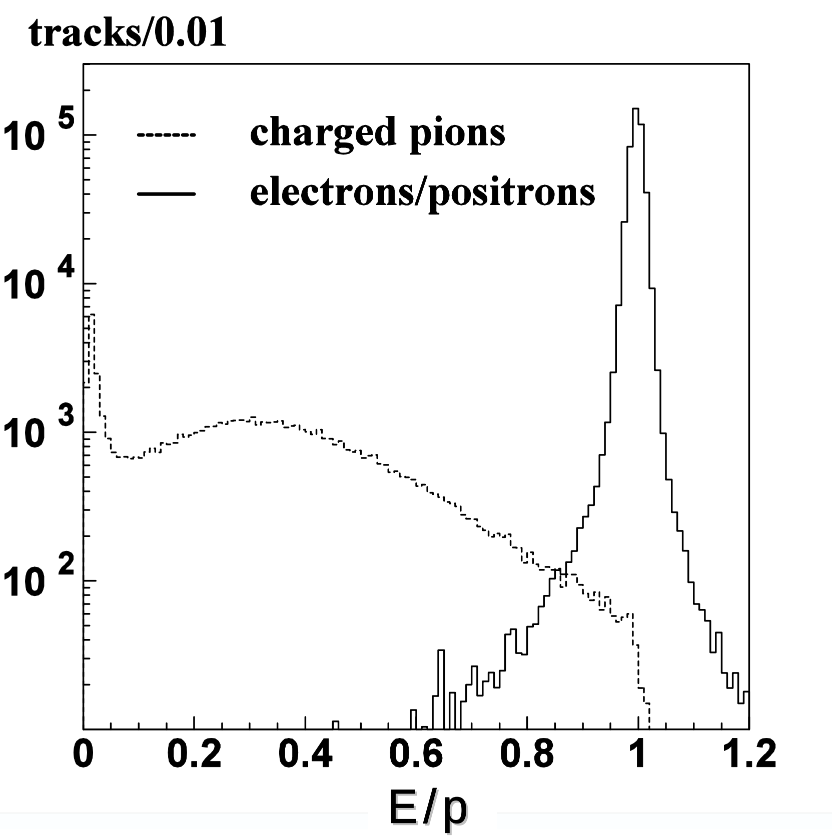
- Using $K_{3\pi^0}$ for normalization channel

Selection

- 2 tracks events (decays) in the magnetic spectrometer
  - two tracks with different charges coming from a common vertex
  - Time difference of the tracks < 6 ns
  - Minimal distance between tracks cda< 3 cm
  - Vertex located in the decay region: 8 m < z < 33 m
  - Tracks in the detectors aperture
  - Minimal momentum of each track p_{min} = 10 GeV
  - Minimal distance between tracks in LKr D_{lkr} = 25 cm
  - Sum of the momenta of the two tracks P > 60 GeV
- K_{e3} decays
  - E/p >0.93 for at least one of the tracks

Inefficiency for identification of K_{e3} at $E/p>0.93$

"Clean" pions and electrons

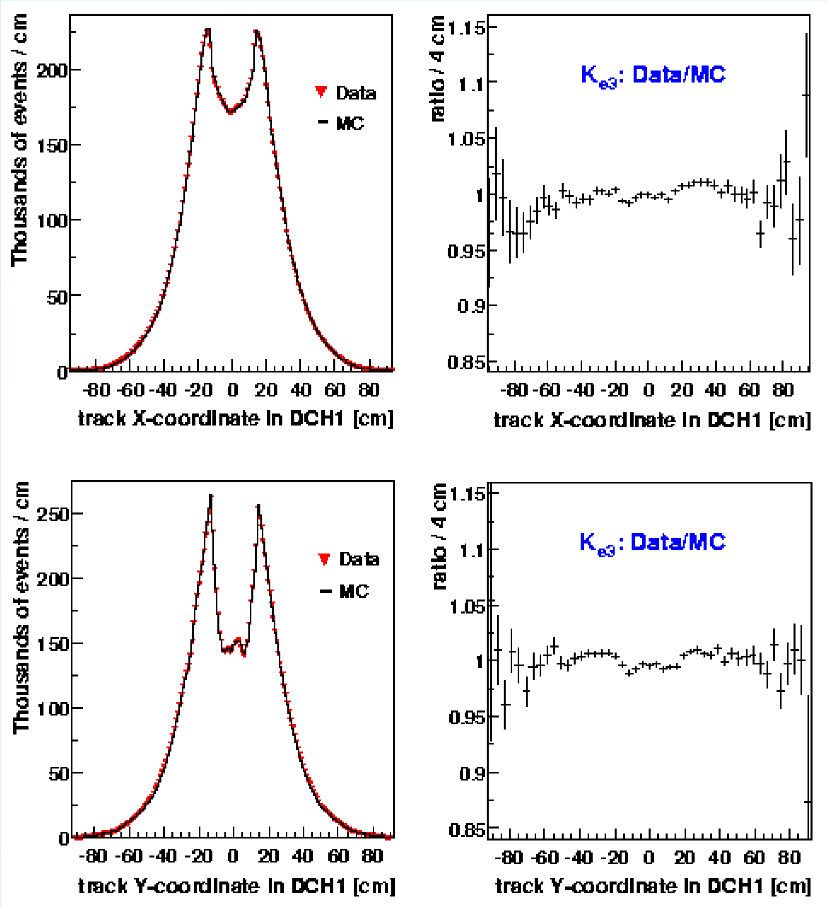


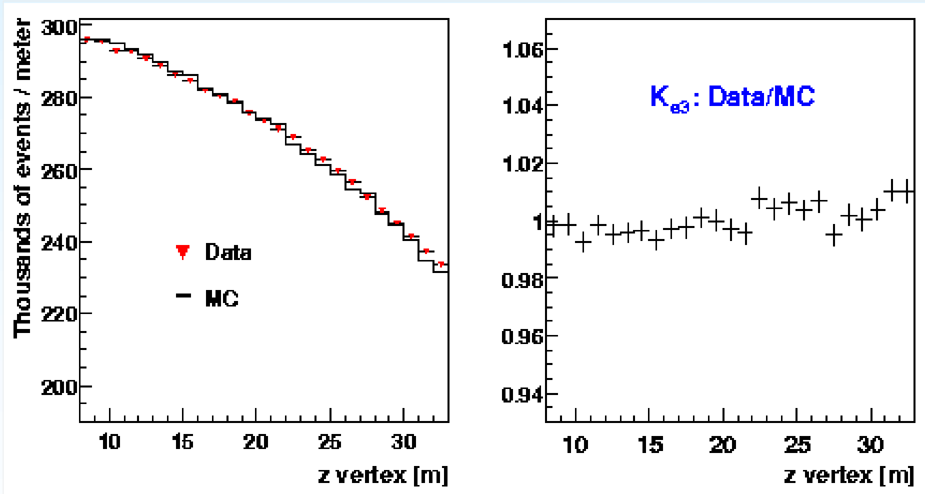
- Obtaining "clean" pions by a special selection (requiring the other track to be with $E/p>1.0$)
- Obtaining "clean" electrons by a special selection (requiring the other track to be with $E/p<0.7$)

$W(\pi\rightarrow e)=(0.576\pm0.005)\%$

$W(e\rightarrow\pi)=(0.487\pm0.004)\%$

Data and MC comparison





Systematic uncertainties

Source	$\Delta R_e/R_e$,%
K_L spectrum	± 0.67
normalization	± 0.16
E/p	± 0.05
trigger ineff.	± 0.05
DCH "overflows"	± 0.05
polarity of the magnet	± 0.07
Total	**± 0.70**

Results (1)

- Fraction of K_{e3} to 2-tracks decays

$$R_e = \frac{N_e / Acc(K_{e3})}{N_{2tr} / Acc(K \to 2-tracks)} = \frac{6753478/0.2599}{12592096/0.2412}$$

$R_e = 0.4978 \pm 0.0035$

- Branching fraction of K_{e3}

$Br(K_{e3}) = R_e [1.0048 - Br(K_{3p^0})]$, where $Br(K_{3p^0}) = 0.1992 \pm 0.0070$

is averaged between PDG and the latest KTeV result*

$Br(K_{e3}) = 0.4010 \pm 0.0028(exp) \pm 0.0035(norm)$

***NA48 preliminary:** $Br(K_{3p^0}) = 0.1966 \pm 0.0006 \pm 0.0033$

Results (2)

G V_{us} matrix element*

$$|V_{us}|f_+(0)=0.2146\pm0.0016$$

$$|V_{us}|=0.2187\pm0.0028 \quad \text{at} \quad f_+(0)=0.981\pm0.010$$

*
$$|V_{us}|f_+(0)=\sqrt{\frac{128p^3\Gamma(K^0_{e3})}{G_F^2 m^5_{K^0} S_{EW} I_{K^0}}}$$

$$\Gamma(K^0_{e3})=\frac{Br(K_{e3})}{t(K_L)}$$

$$t(K_L)=(5.15\pm0.04)\times10^{-8}\,s$$

Conclusions

- Parameters of the Dalitz plot in the K_{e3} are measured
  - the slope in the vector form factor is measured with a high precision
  - the scalar and tensor form factors are consistent with zero, the measurement is the most precise up to now
  - results are consistent with a lack of quadratic term in the vector form factor, and at the same time consistent with a Taylor expansion of a pole-dominance form factor
  - such a dipole form factor is in good agreement with data, with a pole mass of M_V=859±18 MeV

Conclusions

- The radiative $K_{e3\gamma}$ branching ratio is measured with a high precision
  - the result is in agreement with the theoretical predictions and does not support the result of KTeV
- The branching ratio of K_{e3} is measured with a high precision
  - results are in agreement with latest experimental results being in conflict with the world average value
  - the V_{us} element of the Cabibbo-Kobayashi-Maskawa matrix is extracted

Publications

1) **Measurement of K^0_{e3} form factors,**
   A. Lai et al., Phys. Lett. B 604 (2004) 1.
2) **Measurement of the radiative K_{e3} branching ratio,**
   A. Lai et al., Phys. Lett. B 605 (2005) 247.
3) **Measurement of the branching ratio of the decay $K_L \rightarrow \pi e \nu$ and extraction of the CKM parameter $|V_{US}|$,**
   A. Lai et al., Phys. Lett. B 602 (2004) 41.

Spare

$\lambda_+ \times 10^3$	$\lambda_0 \times 10^3$
26.0 **±0.7 (stat.)** **±1.0 (syst.)**	**12.0** **±0.8 (stat.)** **±1.5 (syst.)**

G Preliminary
NA48 result on $K_{\mu3}$

KTeV:

$l_+ = 27.45 \pm 1.08 \times 10^{-3}$

$l_0 = 16.57 \pm 1.25 \times 10^{-3}$

PDG:

$l_+ = 33 \pm 5 \times 10^{-3}$

$l_0 = 27 \pm 6 \times 10^{-3}$

Spare

- Results for different polarities of the spectrometer magnet:

	"-"	"+"
λ_+	$(28.6 \pm 0.6) \times 10^{-3}$	$(29.0 \pm 0.6) \times 10^{-3}$
R	$(9.53 \pm 0.10) \times 10^{-3}$	$(9.75 \pm 0.10) \times 10^{-3}$
R_e	0.4980 ± 0.0004	0.4976 ± 0.0004

Spare

$$\ln L = \sum_i \left(d_i \ln f_i - f_i \right) + \sum_i \left(a_{0i} \ln A_{0i} - A_{0i} \right),$$

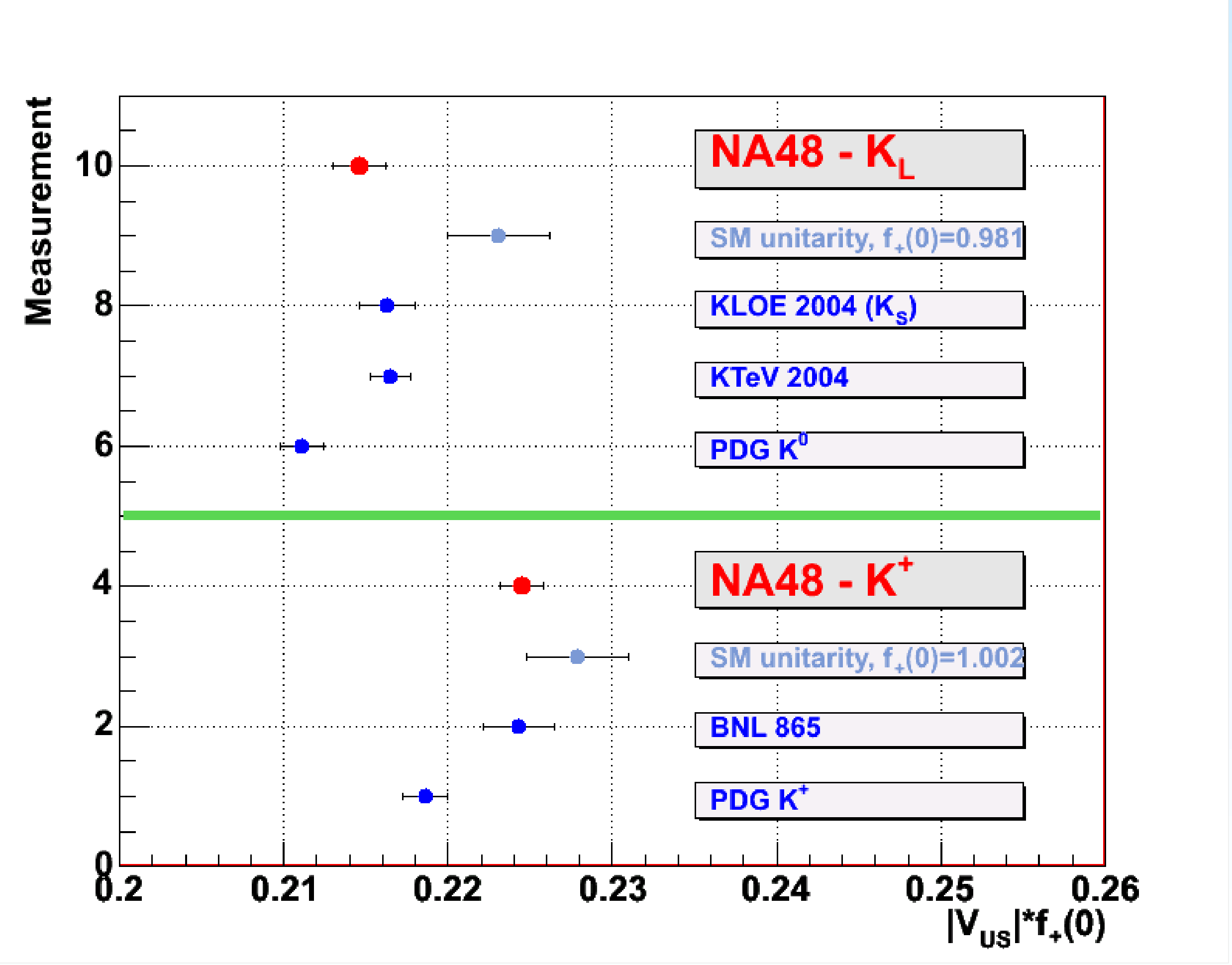
where (for the maximum of the function):

$$f_i = A_{0i} h_i, \qquad A_{0i} = \frac{d_i + a_{0i}}{1 + h_i} \qquad \text{and} \qquad h_i \equiv c\left(1 + \sum_{j>0} w_{ij} P_j\right)$$

In our case:

$$h = c\left(1 + W_1 l_+ + W_2 l_+^2 + W_3 F_S^2 + W_4 F_T^2 + W_5 F_S F_T\right)$$

Spare



Measurement
10
8
6
4
2
0
0.2
0.21
0.22
0.23
0.24
0.25
0.26
$|V_{us}|*f_+(0)$
NA48 - K_L
SM unitarity, $f_+(0)=0.981$
KLOE 2004 (K_S)
KTeV 2004
PDG K^0
NA48 - K^+
SM unitarity, $f_+(0)=1.002$
BNL 865
PDG K^+